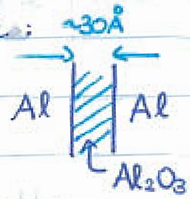
Scanning Tunneling Microscopy (I) [Yazdani]

- Reasons for local probe :
  - ▲ randomly doped system can be inhomogenous
  - ▲ systems close to transition may segregate into different phases
  - ▲ can learn about correlation by measuring response to defects
  - ▲ search for "fluctuating" order.

- Length Scales
  - ▲ Inter-atomic ~Å
  - ▲ e^- wavelength : good metal ~Å , bad metal ~10 Å , semiconductor ~100Å
  - ▲ coorelation length : 100 – 1000 Å .
  - ▲ phase domain : 1000 Å ~ μm.

- Tunneling junction by Giaever (1963) — Aluminum-oxide : ~30Å
  - ▲ Al_2O_3 is "self-limiting" — the layer stop growing at ~30Å



- Tunneling rate govern by Fermi's golden rule

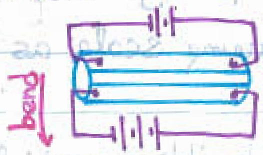
$$I(V,r) \propto \int_{E_F}^{E_F+V} |M|^2 \rho_{tip}\, \rho_{sample}(\varepsilon, r)\, d\varepsilon$$

$|M|^2 \rho_{tip}$ → assume to be const. in ε.

  - ▲ Assume tunneling is elastic
  - ▲ It is possible to use inelastic processes for measurement too.

- Vaccum Tunneling : Binning & Rohrer (IBM-1980)
  - ▲ oxide insulating layer is highly varying in space
  - ▲ The idea of using tunneling for imaging date by to Russell Young (1972)
  - ▲ Key idea is to use piezoelectric elements to move tips
  - ▲ 1V ~ 1 Å , stable voltage ~mV

    ⟹ voltage noise not a problem.



- Tip + sample in vibration isolation. Feedback loop to adjust tunneling current constant.
  - ▲ Vaccum between tip/sample ~ 5-6Å
  - ▲ First example: Si shows 7×7 pattern on (111) surface

- Building STM.
  - ▲ Ultra high vaccum ($\sim 10^{-6}$ torr), vibration isolation, cryogenics
  - ▲ Main problem: noise associate with building vibration (~6 Hz), air-conditioning & pump noise, etc.

- Prefer single crystal, & cleave to nice surface, heat to remove defects, etc.

- Example: Cu (111)
  - ▲ Have surface states manifest as waves, & surface defects create dips in e^- density.

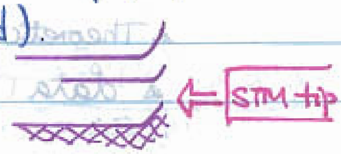
- How clean vaccum need be depends on sample (e.g. Au is tolerating).

- Can fix on particular pixel and measure full $\frac{dI}{dV}$ curve, then scan through pixels.
  - ▲ caveat in data: matrix element $|M|^2$ need be almost invariant across space and voltage.

- Example: scattering through hard wall
  - ▲ From fitting to one-particle wavefunction, can get dephasing scale as function of energy

- Example: building particle-in-a-box (but leaky box!) & observe standing wave of surface states

- STM on GeAs (110) surface
  - ▲ easy to cleave — exposed to UHV.
  - ▲ states at +1.6V dominated by Ga, states at −1.6V dominated by As ⟹ able to distinguish atoms.
  - ▲ Dopants create ~ hydrogenic electronic density profile on top of original profile (it can get more complicated).
  - ▲ However, STM tip can modify (bend) semiconductor band structure.



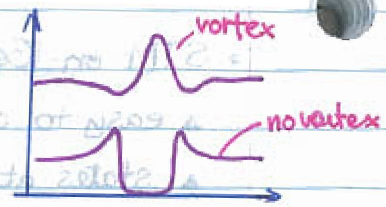
- Example: high-T_N ferromagnet in Mn doped GaAs
  - ▲ Mn creates acceptor states & also institutal defects.
  - ▲ STM indicates that dopants occupy random sites & can have very different local environment
  - ▲ It is possible to do spin polarized STM to observe magnetism directly.

- Example: STM on superconductor
  - ▲ data back to Giaever (Giaever)
  - ▲ detail analysis shows bump & wiggles
    ⟹ indicate strong coupling between e^- & phonon.
    Conclusively shows that conventional SC is phonon mediated.

- Example: STM on $NbSe_2$
  - ▲ STM can reveal SDW. It also gives gap measurement

- Other than mechanics, resolution of STM depends on temperature, since Fermi function enters into eqn. of I

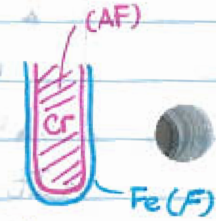
- STM can be used to show vortices in SC
  - ▲ The vortex in $NbSe_2$ shows hexagonal start structure, consistent with BdG eqn.



- STM can also show effect of SINGLE magnetic impurity in SC
  - ▲ Theoretically, it bounds a quasiparticle (mixed e^-/hole) to it.
  - ▲ data:

  - ▲ Picture: spin-dependent potential ⟹ trap quasiparticles

  - ▲ Vortex survives ~ coherent length while impurity effect generally decay quickly.
- Spin-polarized STM
  - ▲ take a usual tip, & add a thin magnetic layer on top of it.



  - ▲ Observed layered magnetization on Cr (an antiferro)
  - ▲ The tip is more magnetically sensitive at specific energy
  - ▲ So far measurement focus on simpler systems
- Inelastic STM.
  - ▲ C_2H_2 on top of Cu(100). See jump at energy iden with vibrational excitation of C_2H_2.